High-resolution radio imaging of young supernovae

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Summary. The high resolution obtained through the use of VLBI gives an unique opportunity to directly observe the interaction of an expanding radio supernova with its surrounding medium. We present here results from our VLBI observations of the young supernovae SN 1979C, SN 1986J, and SN 2001gd. [13]

1 Introduction

In the standard model of radio emission from supernovae, a blast wave is driven into an ionized, dense, slowly expanding wind. As a result, a high-energy-density shell is formed. The relativistic electrons present in this shell spiral along the magnetic field and respond for the observed radio synchrotron emission. The supernova quickly increases its radio brightness with time, due to the increasingly smaller electron column density in the line of sight. When the optical depth at cm-wavelengths is about unity, the supernova reaches its maximum of emission, after which the emission monotonically decreases due

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to expansion losses. Very-Long-Baseline Interferometry (VLBI) observations of radio supernovae are a powerful tool to probe the circumstellar interaction that takes place after a supernova explodes. Indeed, high-resolution radio observations permit us to trace the presupernova mass loss history by directly imaging the structure of the supernova as it expands. The wealth of information includes also a direct estimate of the deceleration of the supernova expansion, estimates of the ejecta and circumstellar density profiles (which has implications on the progenitor system), distortion of the shock front, and the potential observation of Rayleigh-Taylor instabilities. Unfortunately, the usually large distances to radio supernovae makes their VLBI imaging a challenging task, and only radio supernovae that are young, bright, nearby, and rapidly expanding are appropriate VLBI targets. Since high-resolution radio observations of the young supernovae 1993J and 1987A, as well as VLBI observations of the supernova remnants in M82 are covered by other authors in these proceedings, we shall limit our discussion to the cases of SN 1979C, SN 1986J, and SN 2001gd.

2 SN 1979C

SN1979C was discovered on 19 April 1979 in the galaxy M100. It was classified as a Type II Linear supernova, and had an expansion velocity of 9200 km/s, at an age of about 45 days [14]. Its radio emission has been interpreted within the minishell model [3] with some modifications [13]. Recent studies of the environment of the supernova carried out in the optical [20] have put a possible constraint on the mass of the progenitor of 17 to 18 $M_\odot$. Previous VLBI observations of SN 1979C did not resolve the radio structure of the supernova [1]. Nevertheless, the modeling of these radio data showed the observations to be consistent with an undecelerated expansion of the supernova ($r \propto t^m, m = 1$) for the first five years.

The radio light curves of SN 1979C are rather odd, showing a wiggling behavior for almost 20 yr. Recently, the radio brightness of SN 1979C has stopped declining (or even started to increase) and has apparently entered a new stage of evolution [13]. This new trend in the radio light curves of SN 1979C is interpreted as being due to the supernova shock wave having entered a denser region of material near the progenitor star.

Prompted by this apparent new trend in the radio light curves of SN 1979C, we observed the supernova on June 1999 with a very sensitive four-antenna VLBI array at a wavelength of 18 cm. Unfortunately, the VLBI array could not fully resolve the radio structure of SN1979C, and we therefore determined model-dependent sizes for the supernova and compared them with previous results. We estimated the size of the supernova by using three different models: First, an optically thick, uniformly bright disk; second, an optically thin shell of width 30% the outer shell radius; and third, an optically thin ring. (We refer the reader to [10] for details of the modeling.) The best-fit model was an

optically thin shell model, which has an angular size of 1.80 milliarcseconds for the outer shell supernova radius, corresponding to a linear size of $\sim 4.33 \times 10^{17}$ cm. The combination of our VLBI observations ($t \sim 20$ yr, M02 in Fig. 1) and previous ones [1] ($t \sim 5$ yr, B85 in Fig. 1), plus optical observations [5] at $t \sim 14$ yr (F99 in Fig. 1) allowed us to get an estimate of the epoch at which the deceleration started. We estimate that the supernova shock was initially in free expansion ($m = 1.0$) for the first 6 ± 2 yr and then experienced a very strong deceleration, characterized by a value of the deceleration parameter of $m = 0.62$.

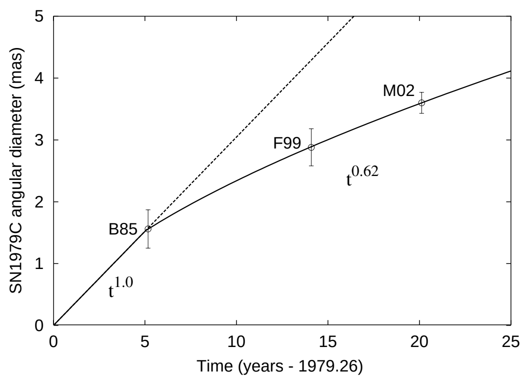

Fig. 1. Angular diameter of SN 1979C, in milliarcseconds, against time since explosion. The solid line indicates a possible expansion, which goes undecelerated ($m = 1$) for the first five years, and strongly decelerated ($m = 0.62$) from then on. See [10] for details.

If this deceleration is solely due to increased resistance from the circumstellar medium (CSM), the mass of the CSM swept up by the shock front, $M_{\rm swept}$, must be comparable to or larger than the mass of ejected hydrogen-rich envelope, $M_{\rm env}$. We estimate $M_{\rm swept} \sim 1.6\,{\rm M}_\odot$, assuming a standard density profile for the CSM ($\rho_{wind} \propto r^{-2}$). Momentum conservation arguments then suggest that the mass of the hydrogen-rich envelope ejected at explosion, $M_{\rm env}$ is no larger than about $0.9\,{\rm M}_\odot$. Those results favor a binary star scenario for SN 1979C, as previously suggested (e.g. [21]). The low value of the hydrogen-rich envelope suggests that the companion of the progenitor star stripped off most of the hydrogen-rich envelope mass of the pre-supernova star prior to the explosion, similar to the situation in SN 1993J.

Another point worth mentioning is the magnetic field in SN 1979C. If we assume equipartition between fields and particles, one expects a minimum magnetic field in the range of 10–80 mG to explain the observed level of radio emission. Since the energy density of the wind magnetic field is not larger than the kinetic energy density in the wind, it follows that $B_w \lesssim (\dot{M} v_w)^{1/2}\, r^{-1}$ for a standard wind. Using a mass-loss rate of $\sim 1.2 \times 10^{-4}$ ${\rm M}_\odot$ yr^{-1} for the progenitor of SN 1979C [8, 23] and a standard pre-supernova wind velocity

v_w of 10 km s^{-1}, we obtain $B_w \lesssim 0.2\,\mathrm{mG}$, which is a factor of 50–400 lower than needed. Therefore, if particles and fields are not very far from equipartition, then compression of the wind magnetic field due to the passage of the supernova shock is not enough to explain the high magnetic fields in the supernova, and another amplification mechanism must be acting. Turbulent amplification, as seems to be the case of SN1993J [15], is likely the most promising mechanism.

3 SN 1986J

The type II SN 1986J exploded in the galaxy NGC891 ($D \approx 10$ Mpc). Unlike most supernovae, it was serendipitiously discovered in the radio more than three years after the explosion. Modeling of the existing observations set the time of the explosion at the end of 1982 or the beginning of 1983 [17, 22]. The supernova reached a peak luminosity at λ6 cm of about 8 times larger than that of SN 1979C, and about 13 times larger than the peak for SN 1993J, becoming one the brightest radio supernovae ever. Based upon its large radio luminosity, the progenitor star was probably a red giant with a main-sequence mass of $20 - 30$ M$_\odot$ that had lost material rapidly ($\dot{M} \gtrsim 2 \times 10^{-4}$ M$_\odot$ yr^{-1}) in a dense stellar wind [22].

VLBI observations made at λ3.6 cm at the end of 1988 showed a shell-like structure for SN 1986J [2]. The authors claimed the existence of several protrusions at distances of twice the shell radius, and with apparent expansion velocities as high as $\sim$ 15000 km s^{-1}. Since these protrusions were twice as far as the mean radius of the shell, it then follows that the main bulk of the shell expanded at roughly 7500 km s^{-1}. Such protrusions have been successfully invoked [4] to explain the coexistence of velocities smaller than 1000 km s^{-1} implied from the observed narrow optical lines [17, 9], and the large velocities indicated from the VLBI measurements.

We used archival VLA and global VLBI observations of supernova 1986J at λ6 cm, taken about 16 yr after the explosion, to obtain the images shown in Fig. 2 (see [16] for a comprehensive discussion). The right panel corresponds to the λ6 cm VLBI image of SN1986J. It shows a highly distorted shell of radio emission, indicative of a strong deformation of the shock front. The apparent anisotropic brightness distribution is very suggestive of the forward shock colliding with a clumpy, or filamentary wind. Note that there are several "protrusions" outside the shell, though just above three times the noise level and at different position angles from those previously reported [2]. Therefore, these protrusions could not be real, but must be just artifacts of the image reconstruction procedure. If this is the case, the disappearance of the protrusions seen in the previous VLBI observations [2] would imply a change in the density profile of the circumstellar wind.

The angular size of the shell of SN 1986J on 21 February 1999 is $\sim$4.7 mas, corresponding to a linear size of 0.22 pc at the distance of SN 1986J. Therefore,

the average speed of the shell has decreased from around 7500 km s^{-1} at the end of 1988 down to about 6300 km s^{-1} at the beginning of 1999, indicating just a mild deceleration in the expansion of the supernova ($m \approx 0.90$). We find a swept-up mass by the shock front of ~ 2.2 $M_\odot$ for a standard wind density profile. This large swept-up mass, coupled with the mild deceleration suffered by the supernova, suggests that the mass of the hydrogen-rich envelope ejected from the explosion was as large as ~ 12 $M_\odot$. This enormous value strongly indicates that the supernova progenitor likely kept intact most of its hydrogen-rich envelope by the time of explosion, and favours a single, massive star progenitor scenario for SN 1986J.

We found a minimum total energy for the supernova (at the epoch of our VLBI observations) in the range $(2 - 90) \times 10^{48}$ erg, depending on the ratio of the heavy particle energy to the electron energy. The corresponding values for the magnetic field should then lie in the range $(13 - 90)$ mG, while the circumstellar wind magnetic field cannot exceed ~ 0.3 mG, i.e., it is 40 to 300 times smaller than necessary to explain the observed radio emission. As in the case of SN 1979C, turbulent amplification seems the most promising mechanism.

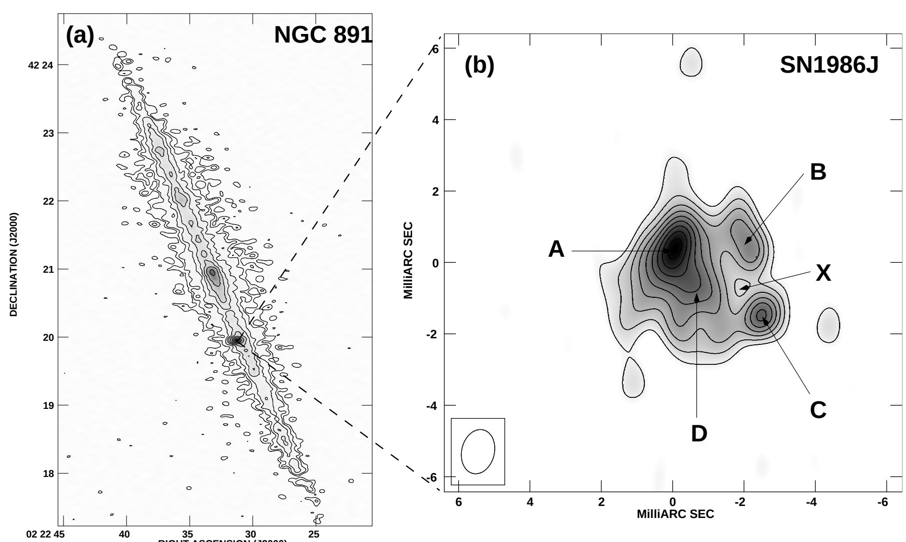

Fig. 2. VLA image (left) of the galaxy NGC 891 and its supernova SN 1986J, at the same frequency (5 GHz) and epoch of the global VLBI observations (right). See [15] for details.

4 SN 2001gd

SN 2001gd was discovered on 24 November 2001 in the galaxy NGC 5033 [6], but its exact explosion date is uncertain. A spectrum of SN 2001gd showed the supernova to be a type IIb event well past maximum light [12]. The spectrum was almost identical to one of SN 1993J obtained on day 93 after explosion [11]. The similarities of the optical spectra of SN 2001gd and SN1993J drove us to observe SN 2001gd at the beginning of February 2002 with the VLA [18]. These and subsequent VLA observations confirmed the suggestion that SN 2001gd was a SN 1993J-like event, displaying a λ6 cm peak luminosity of about twice that of SN 1993J [19].

We carried out high resolution VLBI observations of SN 2001gd at λ3.6 cm, aimed at resolving the supernova structure. Figure 3 shows the image of SN 2001gd obtained from our VLBI observations on June 2002. Since the VLBI observations did not resolve the radio structure of SN 2001gd, we determined an angular size for the supernova using model-dependent estimates. We used the same three models as for SN 1979C. However, none of the models was favoured at this stage and we only inferred an upper limit on the expansion speed of the radio photosphere, which should lie in the range $\sim$ 23000 km s^{-1} to $\sim$ 26000 km s^{-1} at the epoch of our observations ($\sim$ 306 days after explosion) and for an assumed distance to the supernova of 21.6 Mpc.

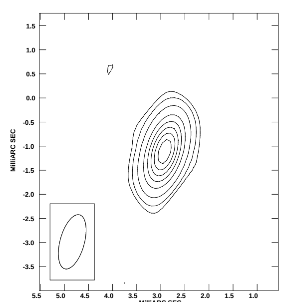

Fig. 3. Radio image of SN 2001gd obtained with GBT+Effelsberg+VLBA on 26 June 2002 (total flux $\sim$ 3.9 mJy; peak $\sim$ 3.3 mJy beam^{-1}; rms noise $\sim$ 20μJy; beam 1.16 $\times$ 0.50 mas, P.A. $\sim -15^{\circ}$).

We plan to follow the evolution of this "twin" of SN 1993J via VLBI observations of SN 2001gd, the first radio supernova for which such monitoring is possible since the SN 1993J event in M 81. Those future observations will likely allow us to determine the deceleration and degree of self-similarity of the supernova expansion, constrain the range of density profiles for the supernova progenitor and the pre-supernova wind, and disentangle its radio emitting structure as it interacts with the circumstellar medium.

We summarize in the table below the most remarkable results obtained from VLA and VLBI studies conducted on the radio supernovae we have

discussed here and, for comparison, those obtained on SN1993J (see Alberdi & Marcaide, this volume).

	SN 1979C	SN 1986J	SN 2001gd	SN 1993J
Distance (Mpc)	16.1 ± 1.3	9.6	21.6?	3.63 ± 0.34
Time since explosion[1](yr)	~ 20.1	~ 16	$\lesssim 1$	~ 8.6
$(L/L_{\rm SN\ 1993J})_{\rm 6cm\ peak}$	~ 1.6	~ 13	~ 2	1
Optically thin phase?	Yes	Yes	Likely yes	Yes
Radio brightness structure	Shell (likely)	Distorted shell	?	Smooth shell
$\dot{M}/10^{-5}$ M$_\odot$ yr^{-1}	$\sim (12-16)$	~ 20	?	~ 5
Deceleration parameter (m)	~ 0.62	~ 0.90	?	~ 0.82
$t_{\rm break}$ (years)	6 ± 2	Not yet	?	~ 0.5
Asymmetric expansion?	No	Yes	?	No ($\lesssim 5\%$)
Circumstellar medium	?	Clumpy	?	Approx. smooth
$M_{\rm swept}/\dot{M}$	~ 1.6	~ 2.2	?	~ 0.4
$M_{\rm env}/\dot{M}$	~ 0.9	~ 12	?	~ 0.6
Explosion scenario	Binary	Single	?	Binary
Magnetic field amplification	Turbulent?	Turbulent?	?	Turbulent?

Table 1. [1]Time since explosion when the VLBI observations were carried out. The tabulated entries below refer to that time.

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